Long-term geospace climate monitoring

Shun-Rong Zhang[1*], Ingrid Cnossen[2], Jan Laštovička[3], Ana G. Elias[4], Xinan Yue[5], Christoph Jacobi[6], Jia Yue[7,8], Wenbin Wang[9], Liying Qian[9] and Larisa Goncharenko[1]

[1] Haystack Observatory, Massachusetts Institute of Technology, Westford, MA, United States
[2] British Antarctic Survey, Cambridge, United Kingdom
[3] Institute of Atmospheric Physics, CAS, Prague, Czech Republic
[4] INFINOA (CONICET-UNT) & FACET, UNT, San Miguel de Tucumán, Argentina
[5] Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, CAS, Beijing, China
[6] Leipzig University, Institute for Meteorology, Leipzig, Germany
[7] NASA Goddard Space Flight Center, Greenbelt, MD, United States
[8] Catholic University of America, Washington, DC, United States
[9] NCAR High Altitude Observatory, Boulder, CO, United States

Climate change is characterized by global surface warming associated with the increase of greenhouse gas population since the start of the industrial era. Growing evidence shows that the upper atmosphere is experiencing appreciable cooling over the last several decades. The seminal modeling study by Roble and Dickinson (1989) suggested potential effects of increased greenhouse gases on the ionosphere and thermosphere cooling which appear consistent with some observations. However, several outstanding issues remain regarding the role of CO_2, other important contributors, and impacts of the cooling trend in the ionosphere and thermosphere: for example, (1) what is the regional variability of the trends? (2) the very strong ionospheric cooling observed by multiple incoherent scatter radars that does not fit with the prevailing theory based on the argument of anthropogenic greenhouse gas increases, why? (3) what is the effect of secular changes in Earth's main magnetic field? Is it visible now in the ionospheric data and can it explain some of the regional variability in the observed ionospheric trends? (4) what is the impact of long-term cooling in the thermosphere on operational systems? (5) what are the appropriate strategic plans to ensure the long-term monitoring of the critical space climate?

Introduction

Growing evidence shows that the upper atmosphere has been experiencing appreciable cooling over the last several decades (e.g., Laštovička, 2017, see Figure 1A). This has been connected to the increase in greenhouse gas concentrations since the start of the industrial age, which drives global warming near the Earth's surface, but causes global cooling in the middle and upper atmosphere (Figure 1B, after Roble and Dickinson, 1989). Greenhouse gases act as a cooling agent in the thermosphere. Infrared emissions by CO_2 at 15 μm and NO at 5.3 μm transfers thermal energy up into the thinner and thinner atmosphere without being trapped as is the case when emitted in the dense lower atmosphere, and therefore these gases provide efficient cooling in the thermosphere. However, the upper atmosphere, especially the ionosphere, is also very responsive to a wide range of other forcings,

both from above, including (long-term) variability in solar irradiation and geomagnetic disturbances, and from below, including various wave activities, violent surface activities (e.g., volcanic eruptions) and gradual Earth magnetic field changes. Detecting, analyzing, and modeling the relatively weak signals over the long term are non-trivial tasks. In the following, we discuss several challenges the community needs to address.

figure 1

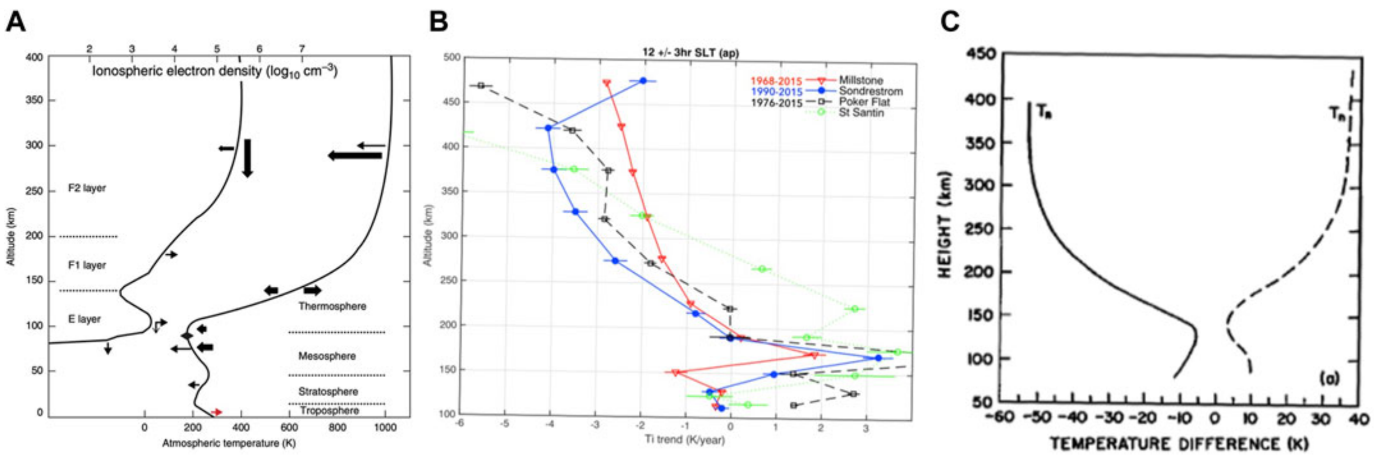

FIGURE 1. Ionospheric and thermospheric long-term trends: **(A)** observations in electron density (solid line on the left) and neutral temperature (solid on the right), after Laštovička et al. (2006); **(B)** incoherent scatter radar ion temperature observations at Millstone Hill (red), Sondrestrom (black), and Poker Flat (blue), after Zhang et al. (2016); **(C)** simulated thermospheric temperature changes due to doubling CO_2 mix ratio at ~ 60 km altitudes (the left solid curve; the right dashed curve is for CO_2 halved), after Roble and Dickinson (1989).

Scientific challenges as future research directions

Cooling is stronger than anticipated CO_2 effects

Satellite drag data indicated that the global average thermospheric density is reducing at a rate of 2–3% per decade at 400 km between the 1960s and 2000s (e.g. Emmert, 2004; 2015). The CO_2 trend at 105–110 km was 7–8% per decade from 2004 to 2012 as reported by Yue et al. (2015); Rezac et al. (2018) using TIMED SABER data. This rate is noticeably larger than a General Circulation Model (GCM) simulation, and the corresponding simulated density trends appear to be smaller than indicated by observations (Emmert et al., 2008). The long-time series of CO_2 measurements in the thermosphere are currently not available to provide adequate trend analysis, and the modeling results have not been fully validated.

Dramatic differences were found in the trends determined from incoherent scatter radar (ISR)-based ion temperature (Ti) at multiple locations (Zhang et al., 2011; Oliver et al., 2013; Zhang and Holt, 2013; Ogawa et al., 2014; Zhang et al., 2016) and trends inferred from model simulations. Figure 1C provides an analysis of the ISR Ti trends measured at Millstone Hill and elsewhere where the trends were centered around ~15K/decade at ~250 km altitudes during the day, equivalent to 75K in 50 years. GCM simulations conducted by, e.g., Roble and Dickinson (1989), Qian et al. (2011), and Solomon et al. (2018) showed consistently that global mean exosphere temperature will drop at 2–5K/decade due to the increasing CO_2 mixing ratio. These results indicated that the observed strong ionospheric cooling could be caused by important additional sources, beyond the greenhouse effect.

Is the gravity wave activity increasing?

Gravity wave (GW) activity has important direct influences on the ionospheric and thermospheric dynamics, and also GW vertical transport of momentum and energy associated with wave dissipation and diffusive mixing through the mesosphere may modify the thermospheric thermal status. Oliver et al. (2013) indicated that GW activity at ionospheric altitudes could be increasing at Millstone Hill. They further speculated this increase could be related to the surface climate change affecting ocean-atmospheric interaction. It is not clear how general this process is as commented by Laštovička (2015). Limited observations on the ground and from space showed that GW trends in the middle atmosphere are very regional and unstable (e.g., Hoffmann et al., 2011; Jacobi, 2014; Liu et al., 2017). To provide direct physical insights whole atmospheric models that can properly resolve GWs may be used to examine the long-term GW trends at different layers of the atmosphere and influences on the ionosphere and thermosphere. Cnossen (2020) reported an initial effort using the Whole Atmosphere Community Climate Model eXtension (WACCM-X), a comprehensive coupled general circulation model, however, with parameterized GWs. High-resolution models explicitly resolving GWs (Becker and Vadas, 2020; Becker et al., 2022), on the other hand, are mechanistic and cannot currently provide a comprehensive view of the whole Earth system, particularly, when the ionosphere is considered.

Long-term trends in geomagnetic activity

The solar activity variability over solar cycles is large, however, a general declining activity since the 1950s (Solar Cycle 19) seems evident. Geomagnetic disturbances are caused by interplanetary coronal mass ejections (ICMEs), which are strongly correlated with solar activity, and high-speed stream (HSS), which is originated from coronal holes, less dependent on solar activity, but appear periodically on the visible solar disk. These disturbances have substantial influences on the upper atmosphere (Mikhailov and Perrone, 2016), including the CO_2 mixing ratio (Liu et al., 2021). Most trend analyses attempted to remove (solar and) geomagnetic activity effects *via* regression with certain (solar and) geomagnetic indices or by using quiet-time data or monthly averages. While the ion temperature Ti and neutral densities are strongly positively correlated with enhanced magnetic disturbances, the peak electron density in the F_2 layer, NmF2, has a very complicated relationship with these indices and therefore it is possible that some trend analysis is, to some degree, contaminated by geomagnetic disturbances. An improved understanding of these effects and sophisticated techniques (e.g., using machine learning algorithms) to deal with this challenge are needed.

The secular change of Earth's magnetic field

The strength of the geomagnetic field has been decreasing at an average rate of 16 nT per year over the past 180 years (Gillet et al., 2013), accompanied by movement of the magnetic poles and magnetic equator (Livermore et al., 2020). Both types of changes are potentially important drivers of long-term change in the upper atmosphere, especially in regions where the magnetic equator and magnetic poles have shifted their positions considerably. These drivers have been recognized in various simulation studies where secular changes of Earth's main magnetic field were considered in addition to long-term trends in trace gas (including CO_2) emissions (e.g., Yue et al., 2008; 2018; Cnossen, 2020; Qian et al., 2021). At Millstone Hill, the magnetic apex latitude has decreased from 57° to 52° and the magnetic dip angle from 71° to 67° between 1950 and 2020 (Figure 2), and less heating related to high latitude magnetosphere-ionosphere coupling is available. The main field change can also modify the ionospheric dynamics including the Sq pattern and the location of equatorial electrojets (Cnossen and Richmond, 2013; Soares et al., 2020; Elias et al., 2021). Since the effects of magnetic field changes vary strongly with location, further studies with different types of observations from diversified locations and model-data comparisons are highly needed to clarify the relative contribution of main field changes to long-term trends.

figure 2

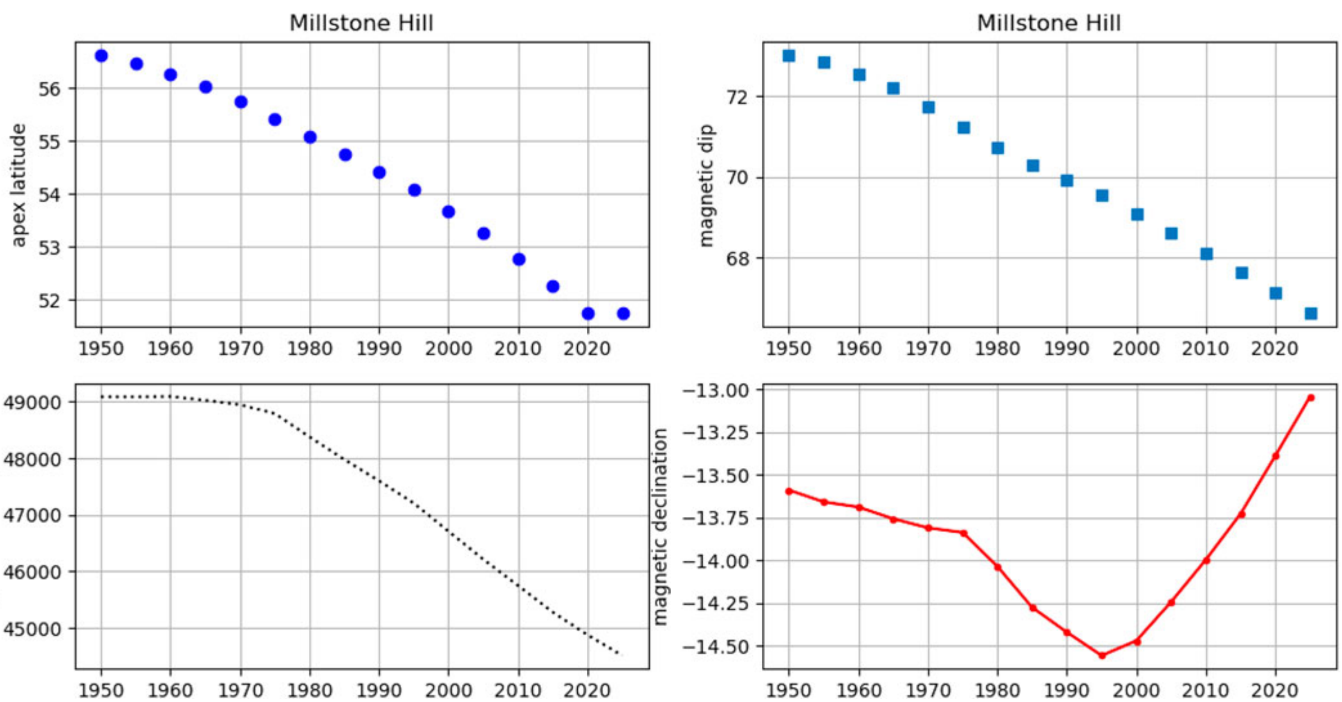

FIGURE 2. Long-term variations of the main magnetic field at Millstone Hill based on the IGRF model.

Impact of the cooling upper atmosphere

Consequences of some long-term changes in the upper atmosphere could appear subtle over short time scales but the accumulated effect can be significant in the long term. For example, incoherent scatter radar observations at Millstone Hill and elsewhere suggested that the ion temperature has decreased by 100 + K above 300 km since the space age. Neutral density at 400 km has reduced by 10–25% for the same time period. Although the ionosphere and thermosphere are subject to larger changes between day and night and across a solar cycle, the increased cooling in the background have gradually become a permanent feature. As the increase in CO_2 concentration will continue in this century and the CO_2 mixing ratio will be likely close to being doubled from its pre-industrial levels by the end of this century, really substantial ionosphere and thermosphere changes can be anticipated.

Potential risks of space debris surviving in orbitals harmful to spacecraft and humans in space become larger due to global cooling and the associated drop in upper atmosphere air density, as this reduces the drag on space debris, increasing its lifetime (Lewis et al., 2011). Brown et al. (2021) indicated that if the 1.5°C warming limit target in the surface atmosphere is met, objects in Low Earth Orbit (LEO) will by 2050 have orbital lifetimes around 30% longer than comparable objects from the year 2000. Radio propagation and communication systems use the ionosphere as a reflection or refraction or transmission medium and they depend on the ionospheric plasma density. For example, sea level monitoring using the altimeter to sense radio wave propagation needs calibration with proper TEC climatology for earlier observations with the single frequency system (Scharroo and Smith, 2010). It is clear that future designs should take into consideration the propagation condition changes (Elias et al., 2017) due to changes in the height and number density of the background ionosphere and in the main magnetic field.

Monitoring upper atmospheric climate change

The scientific community needs to maintain and develop the important capability to monitor space climate over the long-term. Not only long-term data availability but also stability and cross-calibration of the observing system are important aspects.

Various satellite missions provide important observations of neutral density, CO_2 mixing ratio, thermospheric infrared cooling power, GW activity, and topside plasma density (e.g. Emmert, 2015; Yue et al., 2015; Liu et al., 2017; Mlynczak et al., 2018; Cai et al., 2019). The longevity of these missions can be up to 1–2 decades.

Long-term monitoring is relatively easier to achieve using ground-based observational systems, complementary to mission-based *in situ* space observations. These systems are characterized by a clear separation between temporal and spatial ambiguity as well as consistency and stability of observing environment and maintenance. Ionosonde records can span easily over 50 years; continuous ISR data at Millstone Hill available for research started in the 1960s. They remain critically important tools for space climate monitoring.

A list of important ground-based techniques that can enable atmospheric long-term monitoring include magnetometers, ionosondes, incoherent scatter radars, Fabry-Perot Interferometers, All-sky imagers, SuperDARN HF radars, and LIDARs. The communities use them to understand and predict short-term space weather and furthermore to establish climatology and detect climate changes. It is essential that our space weather and space climate monitoring systems can detect a comprehensive set of physical characteristics, from neutral and plasma state parameters (densities and temperatures), to their dynamical behaviors, and to geomagnetic main field and perturbations; it is important also that they are sensitive to spatial variability and time variation in all scales, from short to long-term (Pulkkinen, 2007; Kerridge, 2019).

To maintain efficient long-term investments in monitoring the space climate, proper observational configuration and networks to measure key physical parameters appear a practical approach. It is necessary to balance the needs for building cutting edging new instruments and ensuring the longevity of existing key facilities.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

S-RZ provided the original idea and wrote the first draft, and finalized the article. IC provided comments and edits. Other co-authors (JL, AE, XY, CJ, WW, and LG) read the manuscript and provided comments for improvement.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Benoit Lavraud, UMR5804 Laboratoire d'astrophysique de Bordeaux (LAB), France

Reviewed by:
Veronika Barta, Institute of Earth Physics and Space Science (EPSS, ELKH), Hungary

***Correspondence:** Shun-Rong Zhang, shunrong@mit.edu

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